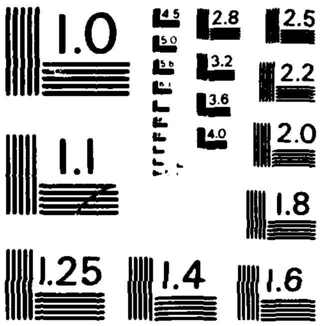
AD-A161 798 MICROWAVE DETERMINATION OF SNOWPACK LIQUID WATER CONTENT(U) COLORADO STATE UNIV FORT COLLINS DEPT OF EARTH RESOURCES H S BOYNE 15 SEP 85 ARO-20107.1-GS 1/1

UNCLASSIFIED DAAG29-83-K-0161 F/G 8/12 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(2)

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ARO 20107.1-GS	2. GOVT ACCESSION NO. N/A	3. RECIPIENT'S CATALOG NUMBER N/A
4. TITLE (and Subtitle) DETERMINATION Microwave ~~Measurement~~ of Snowpack Liquid Water Content		5. TYPE OF REPORT & PERIOD COVERED Final Report 15 Sep 83 - 18 May 85
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) H.S. Boyne		8. CONTRACT OR GRANT NUMBER(s) DAAG29-83-K0161
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Earth Resources Colorado State University FT Collins, CO 80523		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE September 15, 1985 13. NUMBER OF PAGES 38
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) U.S. Army Research Office Post Office Bos 12211 Research Triangle Park, NC 27709		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

DTIC ELECTE DEC 2 1985 S D B

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

THE VIEW, OPINIONS, AND/OR FINDINGS CONTAINED IN THIS REPORT ARE THOSE OF THE AUTHOR(S) AND SHOULD NOT BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, POLICY, OR DECISION, UNLESS SO DESIGNATED BY OTHER DOCUMENTATION.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Snowpack, Liquid Water Content, Microwaves, Measurement Intercomparison, Remote Sensing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

See Reverse

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

MICROWAVE DETERMINATION OF SNOWPACK LIQUID WATER CONTENT

Abstract

The measurement of liquid water in snowpack based on the electrical path length difference in snowpack depth in the region of high dielectric dispersion of water is described. The measurement system consists of a previously described FM/CW microwave system (Ellerbruck and Boyne, 1980) operating at two frequency bands 2-5 GHz and 5-8 GHz. The system is tested, evaluated and itercompared with a dilution measurement technique (Davis, et. al. 1985) in both a laboratory and field environment.

It is found that the two methods of intercomparison are equivalent provided the snowpack is homogeneous and free of stratigraphy. The accuracy of the intercomparison is ±2.5% at the 95% level of confidence.

The intercomparison of the methods is not equivalent when compared in an inhomegeneous stratified snowpack. The microwave system consistently registers a higher volumetric liquid water content than the dilution method. This discrepancy is believed due to differences in the snowpack volumes sampled. In particular, it is believed that ponded water above impermeable layers regions in the snowpack is responsible for the discrepancy. These regions could not be cored successfully for measurement by the dilution method.

MICROWAVE DETERMINATION OF SNOWPACK LIQUID WATER CONTENT

AUTHOR
H.S. BOYNE

SEPTEMBER 15, 1985

FINAL REPORT

U.S. ARMY RESEARCH OFFICE

CONTRACT NO. DAAG 29-83-K-0161

DEPARTMENT OF EARTH RESOURCES

COLORADO STATE UNIVERSITY

Approved for public release; distribution unlimited

The views, opinion, and/or findings contained in this report are those of the author and should not be construed as an official Department of the Army position, policy, or decision unless so designated by other documentation.

Table of Contents

MICROWAVE DETERMINATION OF SNOWPACK LIQUID WATER CONTENT

Abstract

The measurement of liquid water in snowpack based on the electrical path length difference in snowpack depth in the region of high dielectric dispersion of water is described. The measurement system consists of a previously described FM/CW microwave system (Ellerbruch and Boyne, 1980) operating at two frequency bands 2-5 GHz and 5-8 GHz. The system is tested, evaluated and intercompared with a dilution measurement technique (Davis, et al. 1985) in both a laboratory and field environment.

It is found that the two methods of intercomparison are equivalent provided the snowpack is homogeneous and free of stratigraphy. The accuracy of the intercomparison is ± 2.5% at the 95% level of confidence.

The intercomparison of the methods is not equivalent when compared in an inhomogeneous stratified snowpack. The microwave system consistently registers a higher volumetric liquid water content than the dilution method. This discrepancy is believed due to differences in the snowpack volumes sampled. In particular, it is believed that ponded water above impermeable layered regions in the snowpack is responsible for the discrepancy. These regions could not be cored successfully for measurement by the dilution method.

MICROWAVE DETERMINATION OF SNOWPACK LIQUID WATER CONTENT

I. Introduction

Research on the interaction of electromagnetic (em) waves with snowpack has been conducted over the last several years in an attempt to understand the response of em waves to snowpack and to use this interaction to infer or predict the physical state of snowpack, such as depth, water equivalence, and liquid water content.

Snowpack is a dynamic medium continually undergoing changes in density, grain size and shape, stratigraphy, water equivalence, and liquid water content. These changes are driven by radiation and advection processes and storm patterns. Within this spectrum of changing snow conditions, the physical characteristics of liquid water content and density have considerable impact on the interaction of electromagnetic waves with snowpack. The modification of the electromagnetic interaction is brought about by the differences in the dielectric properties of water and ice. At a frequency of 10 GHz, the relative dielectric constants of water and ice at 0°C are 40 and 3.15, respectively, and the rates of attenuation are 4×10^3 Np/meter and 5×10^{-2} Np/meter, respectively (Stiles and Ulaby, 1980a). The relative dielectric constant of dry snow having a density of 350 kgm/m^3 is 1.8. Depending on the liquid water content, snowpack can change from a relatively lossless dielectric to a high loss dielectric. The changes in the dielectric properties can affect the response of both active and passive microwave systems.

Several experiments have been conducted to study the interaction of electromagnetic waves with snowpack (Ellerbruch and Boyne, 1980; Stiles and Ulaby, 1980a,b; Ulaby and Stiles, 1980; Chang et al., 1980; Mätzler et al., 1980; Linlor, et al. 1980). Active radar measurements have been reported at frequencies in the range 1 to 37 GHz, while passive radiometric measurements have been made in the range 5 to 94 GHz. These experiments have shown that the interaction of em waves with snowpack is governed by both surface and volumetric effects of the snowpack and may be influenced by the underlying ground surface. The degree to which volumetric effects play a role is dependent on the snow wetness, stratigraphic layering, grain size, and the observing frequency.

The major difficulty with these experiments is that the snowpack scene is too complex to allow a rigorous quantitative evaluation of the electromagnetic response to snowpack water equivalence and liquid water content. In all experiments the snow medium was inhomogeneous and stratified. It contained snow in several different stages of metamorphism ranging from depth hoar near the ground-snow interface to melt-freeze near the snow-air interface.

The generation of liquid water in snowpack is dynamic and commonly exhibits spatial, volumetric and temporal variations, especially in layered snowpack (Colbeck, 1978; Wankiewicz, 1979). In situ measurements are difficult and the permeability, thickness and areal extent of buried crusts and ice layers is unknown. Thus, while experiments in wet snowpack have been conducted, the inability to establish spatial and temporal liquid water profiles in the pack has limited the interpretation of the results (Kong, et al. 1980).

Experiments specifically designed to measure the dielectric properties of snow containing liquid water under controlled laboratory conditions have been conducted (Hallikainen et al., 1985; Sweeny and Colbeck, 1974). However, the measurements were made to compare the dielectric properties of wet snow with various dielectric mixing models rather than developing methodology to measure liquid water content in a snowpack environment. Direct measurements of liquid water content in snowpack, which are considered reliable, are the freezing calorimeter technique (Jones et al., 1980), the capacitance technique (Ambach and Denoth, 1972, 1980), and the dilution method (Davis et al., 1985). These techniques sample only a limited volume of snowpack, which is not necessarily representative of the entire snowpack.

The measurements described in this report represent attempt to determine liquid water content of a large snowpack volume and account for variations of liquid water within the snowpack. A measurement system is described which is sensitive to the electrical path length between the top and bottom of the snowpack. A three component model for snowpack is developed where the electrical path length through the snowpack is different in two different frequency bands due to the dielectric dispersive property of water. These differences are detectable and form the basis of a measurement instrument to determine liquid water content in snowpack.

The purpose of the study is to test and evaluate the model by developing a microwave system to measure liquid water in snowpack. The microwave measurements are intercompared with a dilution measurement method which has been described, tested and analyzed previously (Davis, et al. 1985).

II. Electrical Path Length Model (EPLM)

Consider a snowpack consisting of ice, air, and liquid water. The volumetric liquid water content is restricted to be not greater than 10%. This regime is typical of a well-drained "ripe" snowpack.

The dielectric properties of the snowpack are treated as a lumped homogeneous system. That is, the three components of the mixture (ice, air, and water) are lumped into layers each of which is considered dielectrically homogeneous (Colbeck, 1980). The porosity is defined as $\phi = \theta_a + \theta$, where θ_a and θ are the volumentric contents of air and water, respectively, and

$$\rho_s = (1 - \phi)\,\rho_i + \theta\rho_w + \theta_a\rho_a \approx (1 - \phi)\,\rho_i + \theta\rho_w$$

where

ρ_s = density of snow

ρ_i = density of ice (0.917 Mg/m^3)

ρ_w = density of water

ρ_a = density of air

The relative dielectric constants of snow, ice, air, and water are ε_s, ε_i, and ε_w, respectively, and the electrical path length through a vertial section of the snowpack is

$$\sqrt{\varepsilon_s}\,d_s = \sqrt{\varepsilon_a}\,d_a + \sqrt{\varepsilon_i}\,d_i + \sqrt{\varepsilon_w}\,d_w \qquad (1)$$

For a unit cross sectional area, the depths of each constituent are numerically equal to their volumetric contents; $d_a = \theta_a$ = depth of air; $d_w = \theta$ = depth of water; and $d_i = 1 - \phi$ is the depth of ice. Since $1 - \phi + \theta + \theta_a = 1$, d_s represents unit snow depth.

Thus,

$$\sqrt{\varepsilon_s} = \sqrt{\varepsilon_a}\theta_a + \sqrt{\varepsilon_i}\ (1 - \phi) + \sqrt{\varepsilon_w}\theta_w \qquad (2)$$

In the microwave region of 1-12 GHz, ε_a and ε_i are frequency independent. ε_w is, however, frequency dependent.

Equation (2) is the basis of comparison with other data. Figure 1 is a comparison with the data of Cumming (1952) and Sweeny and Colbeck (1974) for dry snow (see Colbeck, 1980). Figure 2 compares the data of Ambach and Denoth, and the electrical path length model for $\rho_s = 0.32$ Mg/m^3, ε_w = 87.91 corresponding to a frequency of 20 MHz, which was used by Ambach and Denoth. Figure 3 is a comparison of the Polder-Van Santen model calculation (0-10%) developed by Colbeck (1980) and the electrical path length model for $\rho_s = 0.32$ Mg/cm^3, with $\varepsilon_w = 87.91$. The agreement between the electrical path length model and the Ambach and Denoth data is quite reasonable. Similarly, the comparison of Figure 3 shows a maximum discrepancy of 6% at $\theta = 10\%$.

III. Experimental Procedure

The FM-CW radar operating in the range 1-12 GHz is sensitive to the electrical path length in a snowpack. This observation has been used to measure snowpack water equivalence of dry snowpack by measuring the frequency separation between reflections of swept frequency microwaves at the top and bottom of the snowpack (Ellerbruch, and Boyne 1980). The governing equation is restated here

$$\Delta f = K\sqrt{\varepsilon_s}\,d_s \qquad (3)$$

where ε_s is the dielectric constant of snow, d_s is the depth of snow and $K = \frac{4(f_2-f_1)f_n}{c}$ is a system constant with f_2-f_1 the microwave frequency

band actually swept, f_n the sweep frequency and c the speed of light.

Writing equation (1) for two frequency bands, α and β, we have

$$\sqrt{\varepsilon_{s\alpha}}\, d_s = \sqrt{\varepsilon_a}\, d_a + \sqrt{\varepsilon_i}\, d_i + \sqrt{\varepsilon_{\omega\alpha}}\, d_\omega$$

$$\sqrt{\varepsilon_{s\beta}}\, d_s = \sqrt{\varepsilon_a}\, d_a + \sqrt{\varepsilon_i}\, d_i + \sqrt{\varepsilon_{\omega\beta}}\, d_\omega$$

Subtracting these equations, we have

$$d_\omega = \frac{\left(\sqrt{\varepsilon_{s\alpha}} - \sqrt{\varepsilon_{s\beta}}\right) d_s}{\sqrt{\varepsilon_{\omega\alpha}} - \sqrt{\varepsilon_{\omega\beta}}} \tag{4}$$

$\varepsilon_{\omega\alpha}$ and $\varepsilon_{\omega\beta}$ are determined by averaging the dielectric constant over the frequency band of interest, i.e.,

$$\varepsilon_w (f_2 - f_1) = \varepsilon_{\omega\infty} + \frac{\varepsilon_{\omega o} - \varepsilon_{\omega\infty}}{f_2 - f_1} \int_{f_1}^{f_2} \frac{df}{1 + (f/f_m)^2} \tag{5}$$

where $\varepsilon_{\omega o} = 87.91$, $\varepsilon_{\omega\infty} = 4.9$, and $f_m = 8.51 \times 10^9$ Hz at a temperature of 0°C.

Substituting equation (3) into equation (4) gives

$$d_\omega = \frac{\Delta f_\alpha / K_\alpha - \Delta f_\beta / K_\beta}{\sqrt{\varepsilon_{\omega\alpha}} - \sqrt{\varepsilon_{\omega\beta}}} \tag{6}$$

where Δf_α and Δf_β are measured on the same volume of snowpack.

Assuming the same system constant K for both frequency bands, a frequency difference of 30 to 60 Hz can be expected for a 1% volume of liquid water assuming the two microwave frequency bands to be 2-5 GHz, and 5-8 GHz, the sweep frequency 150 Hz and a snow depth 0.5 m to 1 m.

IV Estimation of Measurement Accuracy

Equation 6 can be analyzed to estimate the accuracy of the microwave measurement method. The error associated with the determination of d_ω is

$$\left|\frac{\delta d_\omega}{d_\omega}\right| = \left|\frac{\delta K}{K}\right| + \frac{2\left|\delta(\Delta f_{\alpha\beta})\right|}{\left|\Delta f_\alpha - \Delta f_\beta\right|}$$

where it has been assumed that $K_\alpha = K_\beta$ and that the errors associated with Δf_α and Δf_β are comparable. The error in K is

$$\left|\frac{\delta K}{K}\right| = \left|\frac{\delta(f_2 - f_1)}{f_2 - f_1}\right| + \left|\frac{\delta f_n}{f_n}\right|$$

Measurements of the voltage controlled frequency sweep, $f_2 - f_1$, are reproducible in the laboratory to an accuracy of ± 0.1% and f_n is reproducible to ± 0.1% (99% confidence interval). Therefore,

$$\left|\delta K/K\right| = 0.2\% \quad .$$

Laboratory reproducibility of Δf_a or Δf_β is ± 5 Hz. For Δf_α = 30 Hz per 1% change in the liquid water content, we see that the error associated with $\delta K/K$ is negligible in comparison to $\left|\delta(\Delta f)//\Delta f_\alpha - \Delta f_\beta\right|$ and

$$\left|\frac{\delta\ d_\omega}{d_\omega}\right| \approx 2\left|\frac{\delta \Delta f}{\Delta f_\alpha - \Delta f_\beta}\right|$$

Figure 4 shows the relative error as a function of liquid water content, the error being ± 33% at d_ω/d_s = 1% and 3.3% at d_ω/d_s = 10% for the microwave frequency bands of 2-5 GHz and 5-8 GHz.

Dilution Method:

The analytical estimate of errors with the dilution method has been analyzed by Davis et al. (Davis, et al. 1985). They estimate the errors due to the combined measurements of the conductivity and mass of the solution, snow and the mixture to be

$$\left|\delta X_\omega\right| = 10^{-2}\ S/M + 1.3 \times 10^{-2}\ X_\omega + 6.5 \times 10^{-4}\ \frac{X_\omega^2}{\delta/M}$$

where S is the mass of stock solution, M is the mass of the snow sample, and X_ω is the liquid water mass fraction. For an S/M ratio of between 0.4 and 1.0, the results of 72 laboratory tests give a mean absolute error of 1.2% for X_ω.

V. Description of Experiments

Experiments were conducted in two phases: laboratory cold room measurements and field measurements. The measurements were designed to verify the measurements of liquid-water content in snowpack with the two frequency band FM-CW system.

A. Laboratory Experiments

Snow samples were prepared in an insulated box of dimensions 1 x 1 x 0.5 m (Fig. 5). The box had a false bottom which was composed of ceramic porous plates having an apparent porosity of 54%. The ceramic plates were covered with a metal screen. The bottom of the box contained an outlet to drain off excess water in the snowpack and to provide tension on the snowpack to drain the pack to a specified volume of liquid water. The box was placed in a laboratory cold room capable of temperature regulation from +10 to -18°C.

Microwave antennas were situated to reflect the radiation into the box. The radiation intensity in the box was measured to determine its distribution (Fig. 6). Natural snow was collected and sifted into the box through a screen whose average aperture was 5 mm. The snow was then covered with styrofoam and kept at constant temperature of -1 to -5°C for several days to allow the snow to settle and stabilize. Liquid water was generated by bringing the temperature to 0°C and exposing an aluminum plate placed on top of the pack to infrared radiation generated from one or two lamps. The length of time the snow was irradiated was determined by the volumetric water content desired. Several tests of this process were made to determine the degree of uniformity of liquid water content within the box (Fig. 7).

Microwave measurements were made on the snow sample. The response of the FM/CW signal was displayed on a spectrum analyzer and subsequently recorded on an x-y plotter. Figure 8 shows the response of both the 2-5 GHz and 5-8 GHz signals for a typical run.

Immediately afterwards, three 0.054 m diameter core samples ranging from 0.4 m to 0.5 m in depth were taken for direct measurement of liquid water by the dilution method. The core samples were distributed in such a way that three sets of measurements could be made before the snow had to be redistributed in the box.

B. Field Experiments

Field experiments were conducted at the summit of Cameron Pass at an elevation of 3200 m. Measurements were conducted in the late Spring of 1984 and 1985. The snowpack was at or near equitemperature and the experiments were conducted in a large meadow on level terrain. The general pro-

cedure for the field experiments was to dig an observation pit, generally 1.5 to 2 m deep, so that density, stratigraphy, grain size and type and liquid water content could be measured (Fig. 9). The microwave system was set up near the south wall of the pit. In all field measurements the bottom of the snowpack sample was determined by the insertion of a metal plate from which the microwave signal was reflected.

Microwave measurements were made on a 1 m^2 cross section of snowpack. Since the top 0.5 m of snowpack had considerable structure, including ice lenses (Fig. 9), measurements were also made on the snowpack after removing the top 0.5 m to 0.7 m of snow. The pack at this depth was generally uniform and free of stratigraphy for the remainder of the day of observation. However, night radiation loss usually froze the exposed surface such that the generated liquid water was spatially nonuniform on the day following exposure.

Direct measurements of the liquid water content were made using the dilution technique. Three to five core samples 0.054 m in diameter and 0.4 m to 0.5 m in depth were taken immediately after each microwave measurement. After each microwave and dilution measurement comparison was completed, a new sample volume of snow was prepared.

A pit profile recorded stratigraphy, grain size and type, density and temperature at various depths (Fig. 10 and 11). Density measurements were made with a glacial sampler after each measurement rather than relying on the core measurement since the diameter of the core sampler was small enough to induce systematic errors in the density (Farnes et al., 1982).

VI. Experiment Results

The data for both the laboratory and field experiments which compare the dilution and microwave measurements of liquid water content in snowpack can be found in the Appendix. Tables 1, 2 and 3 summarize the laboratory and field data. Column 3 of the tables represents the liquid water content determined by the dilution method while column 4 is the liquid water content determined by the microwave method on the same snowpack sample. Column 5 represents the deviation and column 6 the variance of each intercomparison. The data in Tables 1 and 2 show reasonable agreement between the two measurement methods. In these comparisons, emphasis was placed on sampling well-drained uniform snow which was free of stratigraphic layering and had a reasonably uniform grain structure typical of a moist equitemperature snowpack.

The comparisons of Table 3, however, were taken in snow that had considerable stratigraphy and large variations in grain structure between layers. It is evident that the two measurement methods are not comparable in this situation. Figures 10 and 11 show the snowpit data for runs 1 through 6 of Table 3. The numbers to the right of the figure correspond to the first six runs made. The depth of snow sampled for each run is also shown. Air temperature was 4°C to 5°C and surface melting was in progress. However, the stratigraphy in the pack maintained its integrity throughout the day. Nighttime temperatures were below freezing creating a hard frozen crust on the snow surface and occasional surface hoar. Because of the ice lenses and sun crust it was difficult to obtain core samples for dilution measurements. Sampling could be done only where the stratigraphy was weakened by percolation of water. Therefore, while the microwave

VI. Experiment Results

The data for both the laboratory and field experiments which compare the dilution and microwave measurements of liquid water content in snowpack can be found in the Appendix. Tables 1, 2 and 3 summarize the laboratory and field data. Column 3 of the tables represents the liquid water content determined by the dilution method while column 4 is the liquid water content determined by the microwave method on the same snowpack sample. Column 5 represents the deviation and column 6 the variance of each intercomparison. The data in Tables 1 and 2 show reasonable agreement between the two measurement methods. In these comparisons, emphasis was placed on sampling well-drained uniform snow which was free of stratigraphic layering and had a reasonably uniform grain structure typical of a moist equitemperature snowpack.

The comparisons of Table 3, however, were taken in snow that had considerable stratigraphy and large variations in grain structure between layers. It is evident that the two measurement methods are not comparable in this situation. Figures 10 and 11 show the snowpit data for runs 1 through 6 of Table 3. The numbers to the right of the figure correspond to the first six runs made. The depth of snow sampled for each run is also shown. Air temperature was 4°C to 5°C and surface melting was in progress. However, the stratigraphy in the pack maintained its integrity throughout the day. Nighttime temperatures were below freezing creating a hard frozen crust on the snow surface and occasional surface hoar. Because of the ice lenses and sun crust it was difficult to obtain core samples for dilution measurements. Sampling could be done only where the stratigraphy was weakened by percolation of water. Therefore, while the microwave

measurements sampled the entire volume including water which was ponded above the stratigraphic layers, the dilution samples were taken in a part of the volume where the pack was draining.

The question of equivalence of these two methods of measurement involves an analysis of variance of the paired comparisons. Tables 4, 5 and 6 summarize the tests of significance using the F test statistic (Mandel, J., 1964). The statistical test compares two models, one in which $X_v(FM) + \varepsilon = X_v(DL) + \delta$ where ε and δ are the random errors associated with each measurement method, and one in which $X_v(FM) + \varepsilon = K + X_v(DL) + \delta$ where K represents a constant difference between the results. The hypothesis to be tested is that $K = 0$.

Table 4, 5 and 6 present the analyses for the data presented in Tables 1, 2 and 3. The analyses show that the test for $K = 0$ is not significant at the 5% level for the data presented in Tables 4 and 5, but is significant for the data presented in Table 6. Therefore, $K = 0$ for the data in Tables 4 and 5 and the measurement of liquid water by the microwave and dilution methods measurements are equivalent. However, $K \neq 0$ for the data in table 6 and the paired comparison show a definite bias. The average variance for the combined paired comparisons of Table 4 and 5 is 1.61 and the standard deviation 1.27. Thus the uncertainty associated with the comparison at the 95% confidence level is $\pm$ 1.96σ or $\pm$ 2.5%.

VII Discussion:

It is apparent that the ability to compare liquid water measurement methods will depend to a large extent on the character of the snowpack. If the pack is homogeneous and free of stratigraphy, reasonable success of intercomparisons can be achieved. If, however, the snowpack is inhomogene-

ous with several stratigraphic layers, it may be difficult to achieve even order of magnitude accuracy due to variations snow texture, liquid water content, liquid water distribution and differences in the sample volumes measured by the different methods. Difficulties of this type have been reported in intercomparisons of several electrical sensors operating at frequencies ranging from 1 MHz to 1.3 GHz (Denoth, et al. 1984). These senors showed agreement when intercompared in wet sand and prepared homogeneous wet snow to within ± 1%, but discrepancies of up to 10% were reported in natural inhomogeneous snowpack.

Water flow through layered snowpack media is understood only qualitatively and in situ measurements of liquid water distribution within the snow are difficult. Wankiewiez (1979) has proposed that flow through layered snow be modeled in such a way that the boundary between two snow layers of different textures and densities will impede, have no effect on or accelerate downward flow depending on the diffential effect of pressure immediately above and below the boundary. Using this model, he discusses the effect of ice layers on flow, treating them as compound horizons. Various likely flow patterns resulting from different combinations of fine- and coarse-grain snow are presented, all of which result in spatially inhomogeneous distributions of meltwater in snowpack. A limited number of observations (Wakahama, 1963, 1968, Wankiewicz and de Vries, 1978) tend to support at least qualitatively, the proposed model. It is, therefore, not surprising that the two methods of measuring liquid water in stratified snowpack do not agree. One can expect ponding of liquid water above impermeable layers which could not be examined with the core sampling technique used for dilution measurements.

Several intercomparisons between the microwave and freezing calorimeter methods of measuring liquid water content were attempted. The freezing calorimeter method was initially intended as the standard for the intercomparisons since the basic principles of the method are well understood. However, the technique is difficult to use unless one is intercomparing single 0.2 Kg to 0.5 Kg samples. The measurement of a single sample with this technique is lengthy and several samples (3 to 5) are needed to obtain a liquid water profile. Also, the technique does not always give successful results. Special precautions must be taken to ensure complete mixing of the working fluid and the snow sample. Finally, the liquid water distribution in a reasonably homogeneous snowpack may vary significantly, requiring several profiles to be taken to account for these variations. Figure 12 shows the results of a prepared smoothed 1.5 m^2 surface which was sprayed with a fine mist of dye and left exposed to solar radiation for approximately 10 minutes. The dark splotches are where meltwater is being generated. It is unlikely that a snow sample of 0.2 to 0.5 Kg of snow used in the freezing calorimeter method would adequately represent even the surface meltwater content.

Initially we proposed to use two sets of frequency bands (2-5 and 5-8 GHz, and 2-6 and 8-12 GHz) for the microwave measurement. However, we were not successful in obtaining adequate response from the 8-12 GHz system except in dry snow. Resent results on the dielectric loss in this frequency range as a function of snow wetness (Hallikainen, et al.; 1985) indicate that the attenuation at 10 GHz is approximately 42 db/m per 1% liquid water content (Hallikainen et al., Fig. 15).

VIII CONCLUSIONS

The objective of this study was to test and evaluate the performance of a swept frequency microwave system in measuring the liquid water content of snowpack, and to intercompare this system with other measurement methods in both a laboratory and field environment.

The study concludes that liquid water content in snowpack can be determined using the microwave system in the 2-5 GHz and 5-8 GHz frequency bands. An analysis of the errors indicates that the measurement can be made with an accuracy of ±10% for volumetric liquid water content greater than 2.5% to 3.5% depending on the choice of system parameters.

Intercomparison of the microwave and dilution method of measurement were conducted. It was found that the two methods were equivalent provided the snowpack was homogeneous and free of stratigraphy. The mean standard deviation of the intercomparison for the laboratory and field measurements, combined was 1.27%, thus, the error associated with the intercomparison was ± 2.5% at the 95% level of confidence.

It was found that the intercomparison was not equivalent in a stratified inhomogeneous snowpack and that a definite bias was evident, the microwave measurement being consistently higher than the dilution measurement. The bias is attributed to the difference in the sample volumes of the two measurements, the microwave measurement sensing a 1 x 1 x 0.5 m volume and the dilution measurement sampling three cores 0.054 m in diameter and 0.5 m depth. Furthermore core samples could not be acquired where the stratigraphic layers were impermeable. These impermeable regions are where ponding of liquid water is most likely to occur.

The attenuation of the microwave signal in the region 8-12 GHz was found to be too large to identify the bottom of the snowpack sample when liquid water was present. The attenuation was not measured with great precision, but is consistent with the attenuation reported by Hallikainen (Hallikainen et al. 1985).

The intercomparison of measurements with the freezing calorimeter was abandoned since the time involved in obtaining a representative liquid water profile in the snowpack sample volume was found to be prohibitive. This method is useful if small volumes are intercompared under well controlled conditions, but loses its utility when the measurement time, such as is necessary for liquid water profile measurements, becomes comparable to the time in which snow conditions such as generation of liquid water and breakdown of layers can be expected to change.

Observation of surface melt using dye indicates that the melt process is not uniform and may depend on the past micrometeorological conditions such as eddy currents resulting in differences in the surface snow texture.

REFERENCES

Ambach, W. and A. Denoth: 1972. Frequenzgang und Relaxationszeiten der Dielectriziteits-tante von Schneepsoben nach dem Modell von Cole-Cole. Acta Physica Austriaca 35, pp. 249-261.

Ambach, W. and A. Denoth: 1980. The Dielectric Behaviour of Snow: A Study versus Liquid Water Content. NASA Workshop on Microwave Remote Sensing of Snowpack Properties, A. Rango, ed., NASA Conference Publication 2153, pp. 69-62.

Chang, A.T.C., A. Rango and J.C. Shiue: 1980. Remote Sensing of Snow Properties of Passive Microwave Radiometry: GSFC Truck Experiment. NASA Workshop on Microwave Remote Sensing of Snowpack Properties, A. Rango, ed., NASA Conference Publication 2153, pp. 169-185.

Colbeck, S.C.: 1978. The Physical Aspects of Water Flow Through Snow. In Advances in Hydroscience (Ven Te Chow, ed.), Academic Press, New York. Vol. 11, pp. 165-206.

Colbeck, S.C.: 1980. Liquid Distribution and the Dielectric Constant of Wet Snow. NASA Workshop on Microwave Remote Sensing of Snowpack Properties, A. Rango, ed., NASA Conference Publication 2153, pp. 21-40.

Cumming, W.A.: 1972. The Dielectric Properties of Ice and Snow at 3.2 Centimeters. Jour. Appl. Phys., Vol. 23, No. 7, pp. 768-773.

Davis, R.E., J. Dozier, E.R. LaChapelle and R. Perla: 1985. Field and Laboratory Measurements of Snow Liquid Water by Dilution. J. Glaciology, in press.

Denoth, A., A. Folger, P. Weiland, C. Mätzler, H. Aebischer, M. Tiuri and A. Sihvola: 1984. A Cooperative Study of Instruments for Measuring the Liquid Water Content of Snow. J. Appl. Phys., Vol. 56, No. 7, pp. 2154-2160.

Elerbruch, D.A. and H.S. Boyne: 1980. Snow Stratigraphy and Water Equivalence Measured with an Active Microwave System. J. Glaciology 26, pp. 225-233.

Farnes, P.E., N.R. Peterson, B.E. Goodison and R.R. Richards: 1982. Metrication of Manual Snow Sampling Equipment. Proc. Western Snow Conference 50th Annual Meeting, pp. 120-132.

Hallikainen, M., F.T. Ulaby and M. Abdelmazik: In press. Dielectric Properties of Snow in the 3 to 37 GHz Range: 1986 IEEE Trans. Ant. Prop.

Jones, E., A. Bruce and S. Howell: 1980: Measurement of Liquid Water Content in a Melting Snowpack Using Cold Calorimeter Techniques. NASA Workshop on Microwave Remote Sensing of Snowpack Properties, A. Rango, Ed., NASA Conference Publication 2153, pp. 41-68.

Kong, J.A., R. Shin, S.L. Chuang and L. Tsang: 1980. Theoretical Models for Microwave Snow Response and Applications to Remote Sensing. NASA Workshop on Microwave Remote Sensing on Snowpack Properties, A. Rango, ed., NASA Conference Publication 2153, pp. 147-168.

Linlor, W.I., J.L. Smith, F.D. Clapp and D.J. Angelekos: 1980. Snow Electromagnetic Measurements. NASA Workshop on Microwave Remote Sensing of Snowpack Properties, A. Rango, ed., NASA Conference Publication 2153, pp. 93-118.

Mätzler, C., E. Schanda, R. Wofer and W. Good: 1980. Microwave Signatures of the Natural Snowcover at Weissf-luhjoch. NASA Workshop on Microwave Remote Sensing of Snowpack Properties, A. Rango, ed., NASA Conference Publication 2133, pp. 203-223.

Stiles, W.H. and F.T. Ulaby: 1980a. Microwave Remote Sensing of Snowpacks. NASA Contract Report 3263, NASA Science and Technical Information Office.

Stiles, W.H. and F.T. Ulaby: 1980b. The Active and Passive Microwave Response to Snow Parameters: 1. Wetness. Journal of Geophysical Research, Vol. 85, No. C2, pp. 1037-1044.

Sweeny, B.D. and S.C. Colbeck: 1974. Measurement of the Dielectric Properties of Wet Snow Using a Microwave Technique. CRREL Res. Rep. 325, Hanover, New Hampshire.

Ulaby, F.T. and W.H. Stiles: 1980. The Active and Passive Microwave Response to Snow Parameters: 2. Water Equivalent of Dry Snow. Journal of Geophysical Research, Vol. 85, No. C2, pp. 1045-1049.

Wakahama, G.: 1963. Infiltration of Meltwater into Snowcover-I. Low Temperature Sciences, Series A, Vol. 21 (Japanese with English Summary) 45-74.

Wakahama, G.: 1968. Infiltration of Meltwater into Snowcover-III. Low Temperature Sciences, Series A, Vol. 26, pp. 77-86.

Wankiewicz, A. and J. de Vries: 1978. An Inexpensive Tensiometer for Snow-Melt Research, J. Glaciology, Vol. 20, pp. 577-584.

Wankiewicz, A.: 1979. A Review of Water Movement in Snow. Proc. Modeling Snow Cover Runoff (S.C. Colbeck and M. Ray, eds.) U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, pp. 222-252.

Table 1. Liquid water in snowpack microwave-dilution comparison.

Microwave Frequency Bands
2-5 GHz and 5-8 GHz

Laboratory Data

Homogeneous Snowpack

	Date	X_v (DL) (vol %)	X_v (FM) (vol %)	Deviation	Variance
1	5 Feb	2.96	3.68	-0.72	0.518
2	6 Feb	3.33	5.56	-2.23	4.973
3	7 Feb	1.26	0.18	1.08	1.166
4	15 Mar	3.10	3.22	-0.12	0.014
5	15 Mar	1.25	3.36	-2.11	4.452
6	20 Mar	1.73	2.10	-0.37	0.137
7	21 Mar	4.10	3.21	0.89	0.792
8	21 Mar	5.95	3.31	2.64	6.970
9	10 Apr	1.64	1.21	0.43	0.185
				$\sum$ = -0.51	19.207

Mean σ = 1.461

Table 2. Liquid water in snowpack microwave-dilution comparison.

Microwave Frequency Bands
2-5 GHz and 5-8 GHz

Field Data

	Date	X_v (DL) (vol %)	X_v (FM) (vol %)	Deviation	Variance
1	1 May	1.27	3.30	-2.03	4.121
2	7 May	1.79	1.70	0.09	0.009
3	8 May	3.08	4.20	-1.12	1.254
4	10 May	3.28	4.15	-0.87	0.757
5	10 May	1.06	1.02	0.04	0.002
6	10 May	2.27	2.22	0.05	0.003
7	16 May	3.19	2.40	1.79	1.624
8	16 May	2.67	3.40	-0.73	0.533
9	23 May	2.40	3.00	-0.06	1.360
10	23 May	4.23	2.53	1.70	3.873
				$\sum$ = -2.68	9.680

Mean σ = 1.027

Table 3. Liquid water in snowpack microwave-dilution comparison.

Microwave Frequency Bands
2-5 GHz and 5-8 GHz

Field Data

	Date	X_v (DL) (vol %)	X_v (FM) (vol %)	Deviation	Variance
1	24 Apr	1.36	10.0	-8.64	Top of pack
2	24 Apr	1.24	4.19	-2.95	Top 15 cm removed
3	24 Apr	1.81	5.60	-3.79	Top cm removed 25
4	1 May	3.73	29.5	-25.77	Top of pack
5	1 May	2.58	13	-10.42	Top 10 cm removed
6	1 May	4.64	20	-15.36	Top cm removed 40
7	7 May	2.76	8.70	-5.94	Top of pack
8	8 May	3.62	7.4	-3.78	Top of pack
9	8 May	2.68	10.3	-7.62	Top of pack
10	10 May	3.37	6.6	-3.23	Top cm removed 30

$\sum = 87.52$

Table 4. Liquid water in snowpack microwave-dilution comparison.

Analysis of Variance

Laboratory Data

Homogeneous Snowpack

	Date	X_v (DL) (Vol %)	X_v (FM) (Vol %)	Deviation v	v^2	Deviation $v-\bar{v}$	$(v-\bar{v})^2$
1	5 Feb	2.96	3.68	-0.72	0.5184	-0.6633	0.44001
2	6 Feb	3.33	5.56	-2.23	4.9729	-2.173	4.7234
3	7 Feb	1.26	0.18	1.08	1.1664	1.1367	1.2920
4	15 Mar	3.10	3.22	-0.12	0.0144	-0.0633	0.00401
5	15 Mar	1.25	3.36	-2.11	4.4521	-2.053	4.2162
6	20 Mar	1.73	2.10	-0.37	0.1369	-0.3133	0.09818
7	21 Mar	4.10	3.21	0.89	0.7921	0.94667	0.89618
8	21 Mar	5.95	3.31	2.64	6.9696	2.6967	7.2720
9	10 Apr	1.64	1.21	0.43	0.1849	0.48667	0.23684
				$\sum = -0.51$		0.00	

Model	Residual DF	Sum of Squares of residuals	Mean square
$v = X_v(FM) - X_v(DL) = 0 + (\varepsilon-\delta)$	9	$\sum v^2 = 19.208$	2.134
$v = X_v(FM) - X_v(DL) = K + (\varepsilon-\delta)$	8	$\sum (v-\bar{v})^2 = 19.179$	2.397
Difference	1	$\sum\Delta = 0.029$	0.029

$F = 0.021$

Ho: $K=0$ $0.95F(1,8) = 5.32$

Ho: $K=0$, OK

Table 5. Liquid water in snowpack microwave-dilution comparison.

Analysis of Variance

Field Data

Homogeneous Snowpack

	Date	X_v (DL) (vol %)	X_v (FM) (vol %)	Deviation v	v^2	Deviation $v-\bar{v}$	$(v-\bar{v})^2$
1	1 May	1.27	3.30	-2.03	4.1209	-1.67	2.7889
2	7 May	1.79	1.70	0.09	0.0081	0.45	0.2025
3	8 May	3.08	4.20	-1.12	1.2544	-0.76	0.5776
4	10 May	3.28	4.15	-0.87	0.7569	-0.51	0.2601
5	10 May	1.06	1.02	0.04	0.0016	0.4	0.16
6	10 May	2.27	2.22	0.05	0.0025	0.41	0.1681
7	16 May	3.19	2.38	0.79	0.6241	1.06	1.194
8	16 May	2.67	3.4	-0.73	0.5329	-0.37	0.1369
9	23 May	2.40	3.02	-0.6	3.6	-3.32	0.1102
10	23 May	4.23	2.53	1.7	2.89	1.97	3.8730
				$\sum$ = -2.68		0.00	

Model	Residual DF	Sum of Squares of residuals	Mean square
$v = X_v(FM) - X_v(DL) = 0 + (\varepsilon-\delta)$	10	$\sum v^2 = 10.551$	1.055
$v = X_v(FM) - X_v(DL) = K + (\varepsilon-d)$	9	$\sum (v-\bar{v})^2 =$ 9.[illegible]33	1.0936
Difference	1	$\sum \Delta = 0.718$	0.718

$F = 0.657$

Ho: K=0 $0.95F(1,9) = 5.12$

Ho:K=0 , OK

Table 6. Liquid water in snowpack microwave-dilution comparison.

Analysis of Variance

Laboratory Data

Homogeneous Snowpack

	Date	X_v (DL) (vol %)	X_v (FM) (vol %)	Deviation v	v^2	Deviation $v-\bar{v}$	$(v-\bar{v})^2$
1	24 Apr	1.36	10.0	-8.64	74.650	0.112	0.1254
2	24 Apr	1.24	4.19	-2.95	8.7025	5.802	33.663
3	25 Apr	1.81	5.55	-3.74	13.988	5.012	25.120
4	1 May	3.71	29.55	-25.79	665.12	-17.04	290.29
5	1 May	4.64	20.02	-15.36	235.93	-6.608	43.666
6	1 May	2.58	13.02	-10.42	108.58	-1.668	2.7822
7	7 May	2.76	8.75	-5.99	35.880	2.762	7.6286
8	8 May	3.62	7.4	-3.78	14.288	4.972	24.721
9	8 May	2.68	10.3	-7.62	58.064	1.132	1.2814
10	10 May	3.37	6.6	-3.23	10.433	5.522	30.492
				$\sum = -87.52$		0.00	

Model	Residual DF	Sum of Squares of residuals	Mean square
$v = X_v(FM) - X_v(DL) = 0 + (\varepsilon-\delta)$	10	$\sum v^2 = 1225.6$	122.56
$v = X_v(FM) - X_v(DL) = K + (\varepsilon-\delta)$	9	$\sum (v-\bar{v})^2 = 459.66$	51.073
Difference	1	$\sum \Delta = 765.98$	765.98

$F = 15.00$

Ho: $K=0$ $0.95F(1,9) = 5.12$

Ho:$K=0$, Not Valid

Figure Capitons

Figure 1: Comparison of electrical path length model with data of Cumming (1952) and Sweeny and Colbeck (1974) (Colbeck, 1980).

Figure 2: Comparison of electrical path length model with data of Ambach and Denoth (1972).

Figure 3: Comparison of electrical path length model with Colbeck (1980), Case I $\rho_s = 0.32$ Mg/m^3 $\varepsilon_w = 87.91$.

Figure 4: Worst case percentage error of microwave measurement of liquid water in snowpack.

Figure 5: Insulated snowbox used for laboratory intercomparisons.

Figure 6: Microwave radiation intensity pattern at top surface of the snowbox. Relative intensity normalized to unity at center.

Figure 7: Example of liquid water distribution in the snowbox; measurements are in percent liquid water by mass.

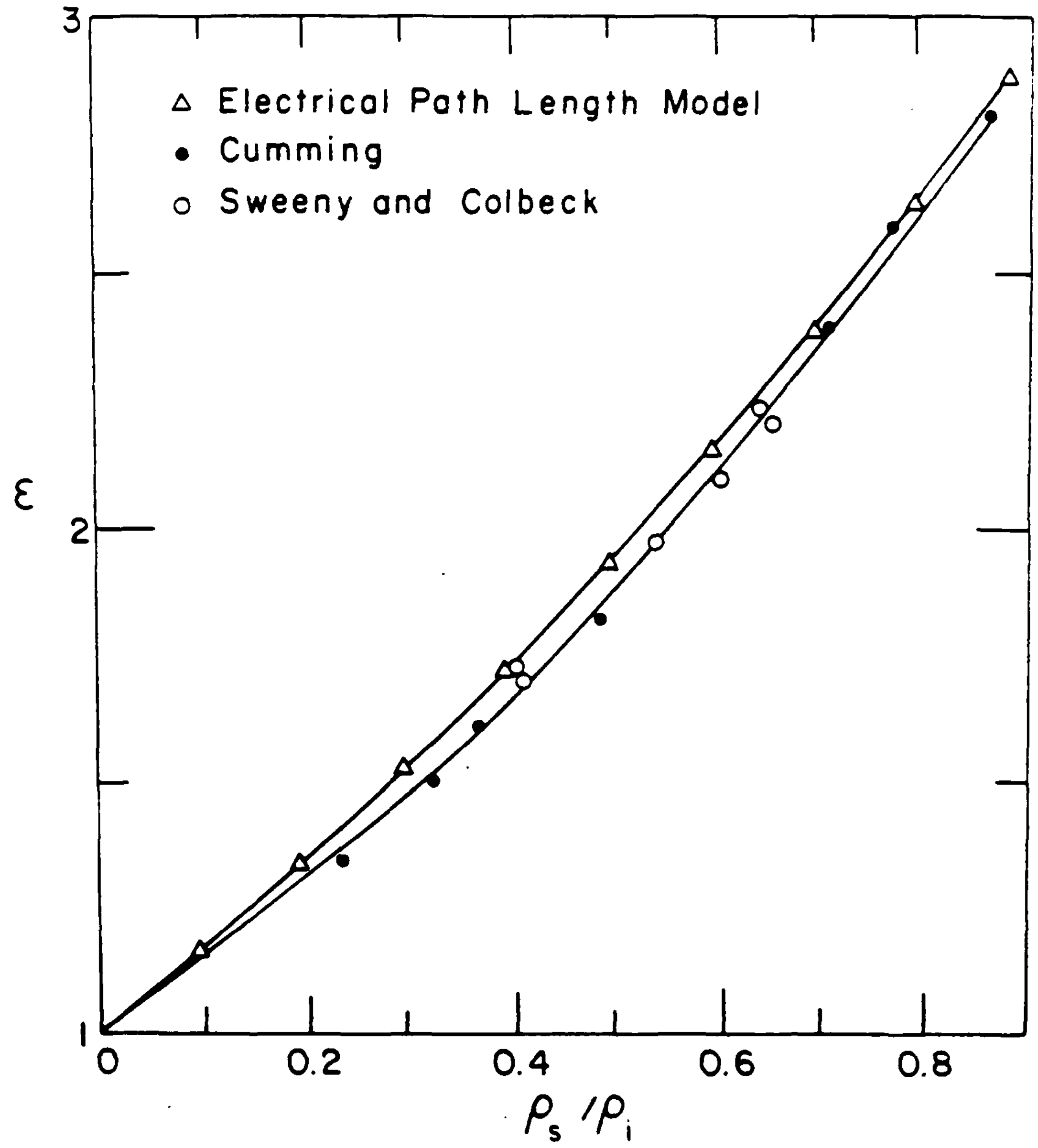
Figure 8: Microwave response to snowpack for 2-5 GHz and 5-8 GHz frequency bands.

Figure 9: Photograph of snowpit used for field measurements. Note several layers on the pit wall.

Figure 10: Pit profile for April 19, Runs 1, 2 and 3 field measurements for inhomogeneous pack are depicted on the right.

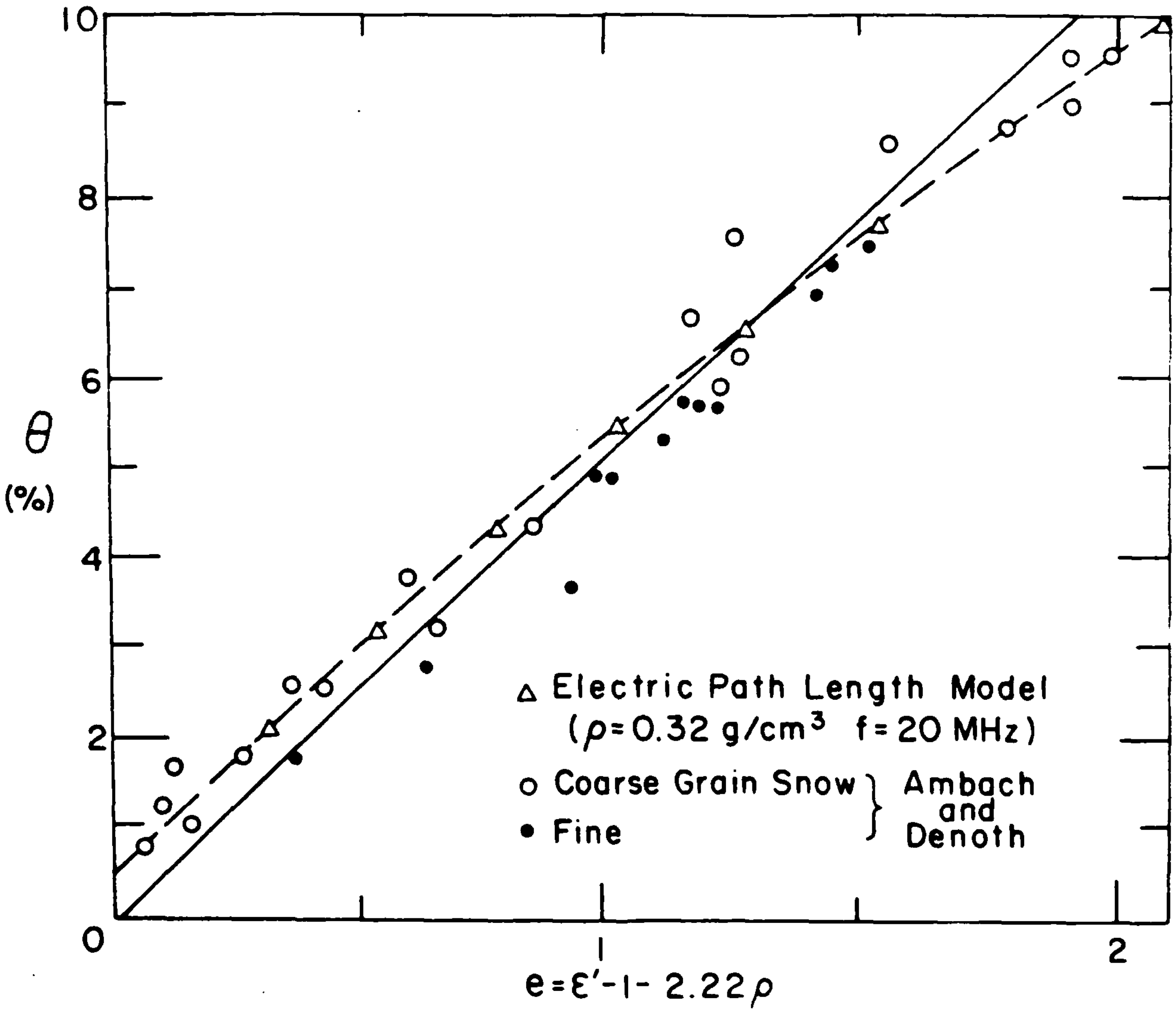
Figure 11: Pit profile for May 1, runs 4, 5 and 6 field measurement for inhomogenous pack are depicted on the right.

Figure 12: Photograph of snow surface after being sprayed with a fine mist of dye. Dark splotches are areas of melting snow.



3
2
1
ε
Electrical Path Length Model
Cumming
Sweeny and Colbeck
0
0.2
0.4
0.6
0.8
ρ_s / ρ_i

Figure 1



10
8
6
4
2
0
θ
(%)
1
2
e=ε′-1- 2.22ρ
△ Electric Path Length Model
(ρ=0.32 g/cm³ f=20 MHz)
○ Coarse Grain Snow
• Fine
Ambach and Denoth

Figure 2

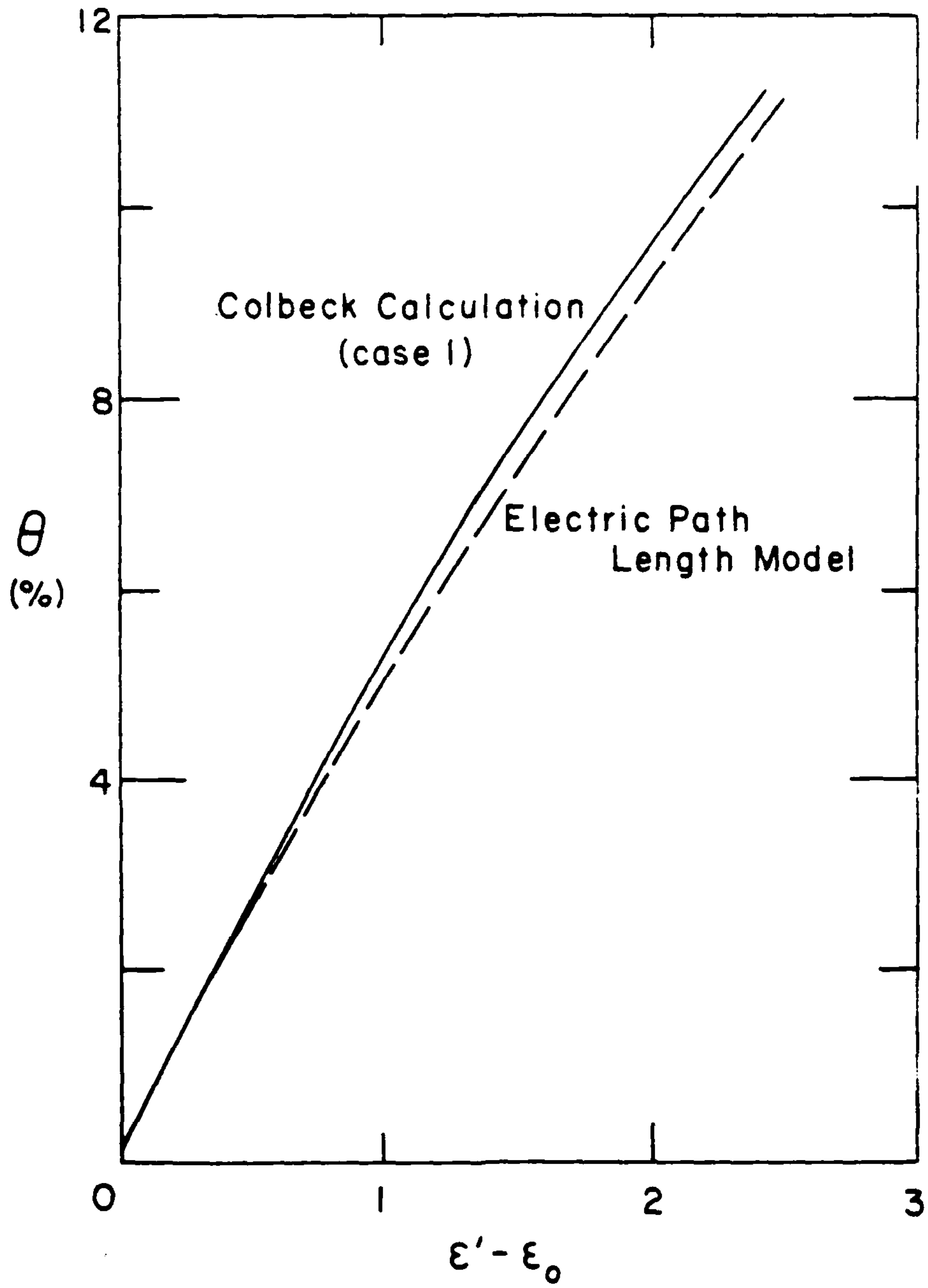

12
8
4
0
1
2
3
θ
(%)
Colbeck Calculation
(case 1)
Electric Path
Length Model
ε′ - ε₀

Figure 3

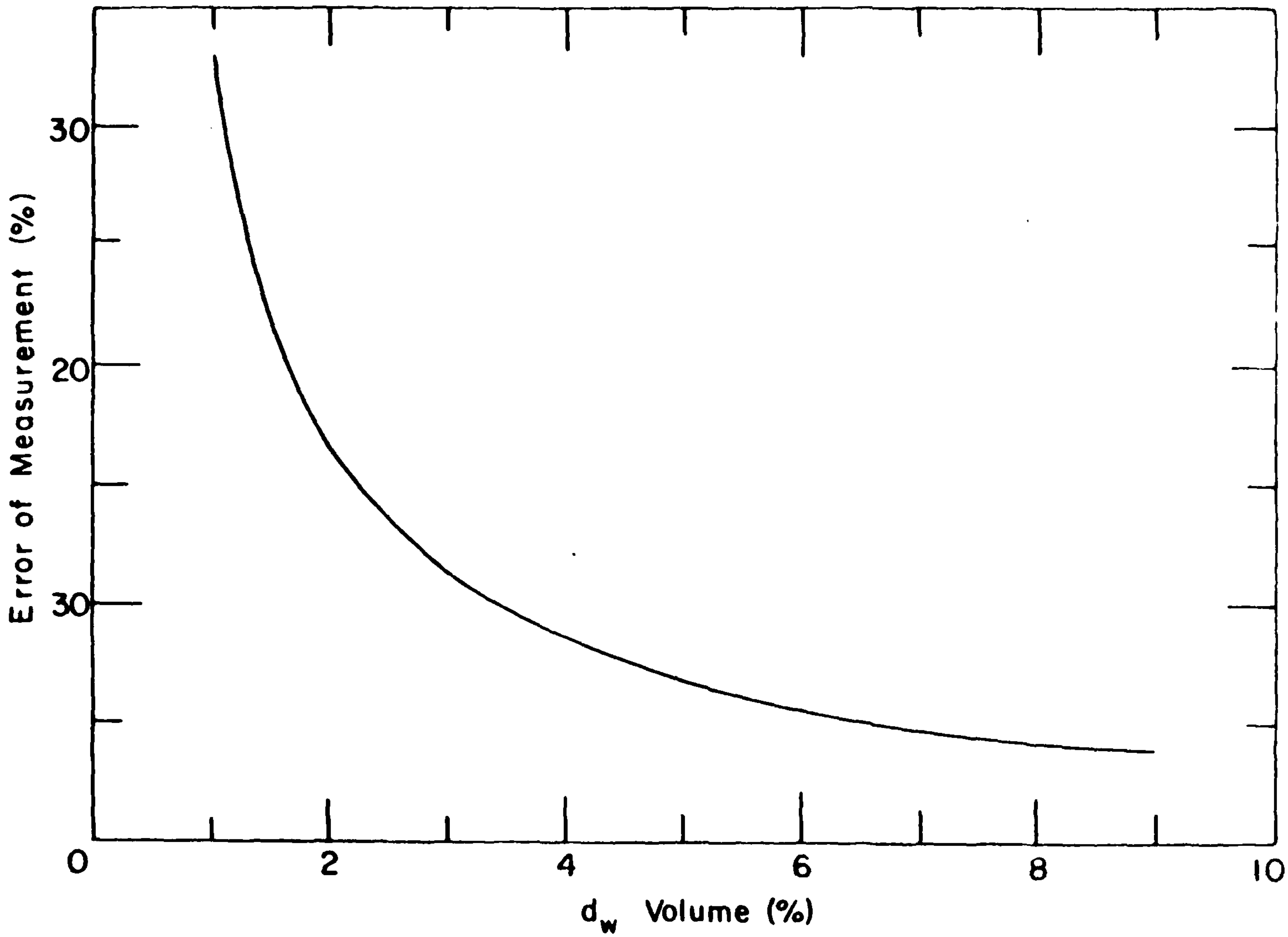


Figure 4

Figure 5

0.21	0.30	0.20
0.36	1.00	0.35
0.21	0.33	0.20

Figure 6

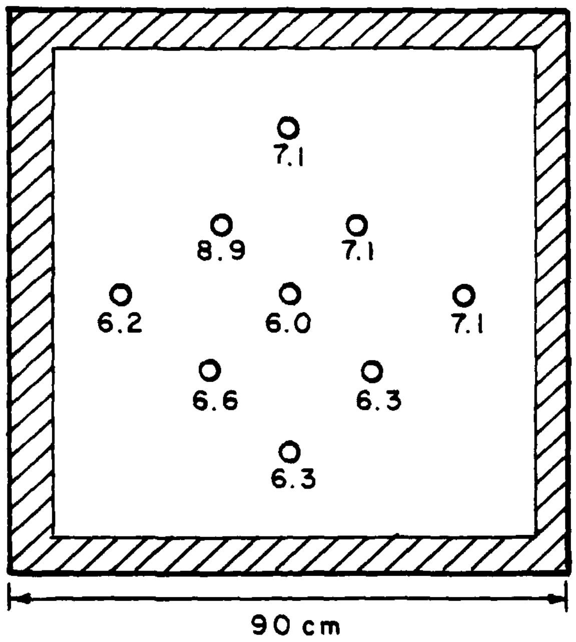
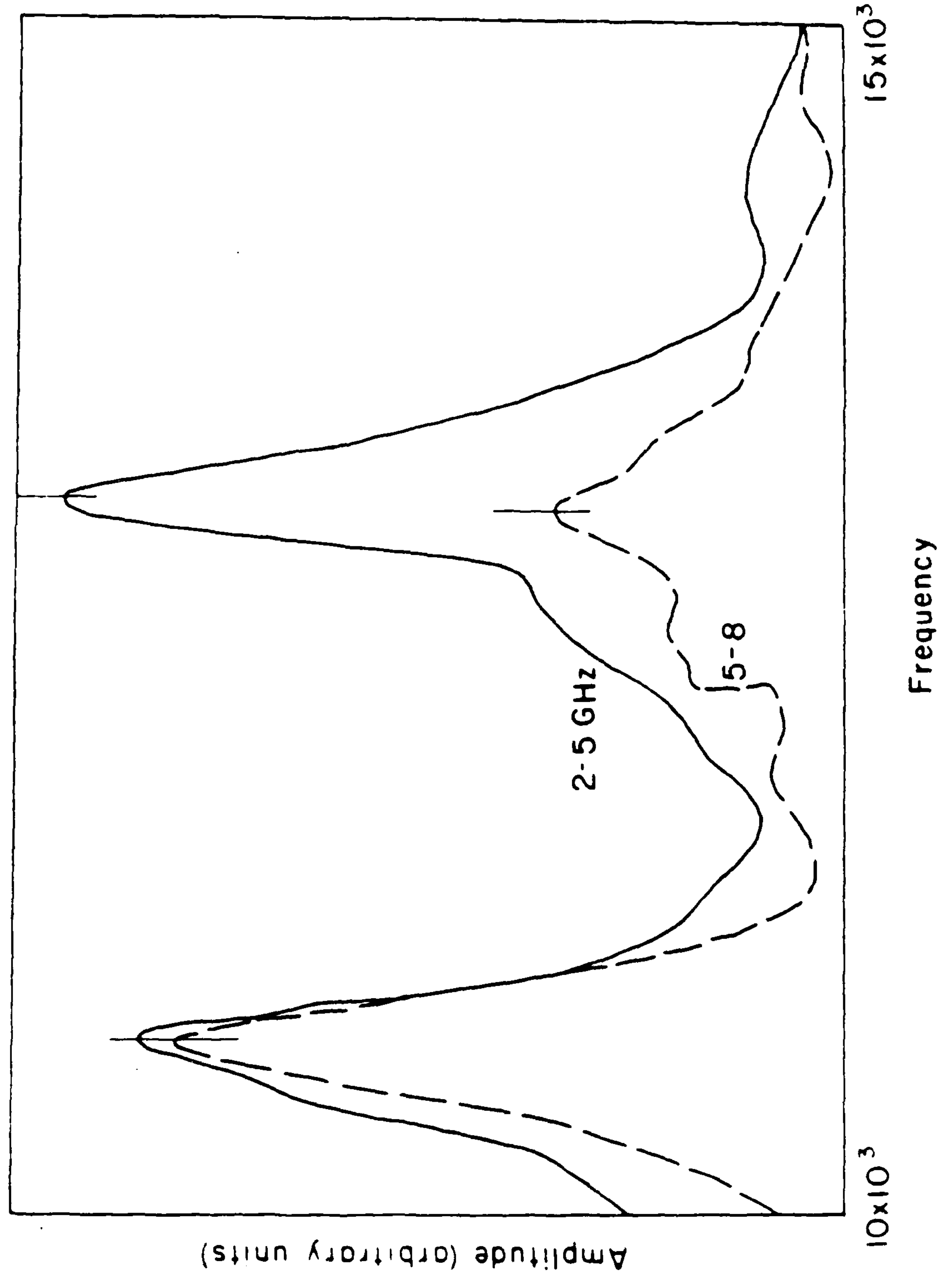


Figure 7



Amplitude (arbitrary units)
10x10³
15x10³
2-5 GHz
5-8
Frequency

Figure 8

Figure 9

STRATIGRAPHY PLOT

DATE:4/24/85 OBSERVER: BOYNE/GEORGE

ELEVATION:3200m TIME: 12:00 SLOPE: LEVEL

DEPTH (cm)	STRATIGRAPHY	GRAIN TYPE	GRAIN SIZE (mm)	DENSITY KG/M^3	TEMP DEG C	
144	--------------					
140	--------------	. . .	<.5mm	108	0	
136	XXXXXXXXXXXXXX	ICE				
132	XXXXXXXXXXXXXX	LENS		270		
128				230		
124		. . .	<.5mm	280		
120				285	0	
116				250		
112	--------------					2
108		o o o	1.0mm	348		
104				500	0	
100	--------------			460		
96				395		3
92		o o o	1.5mm	400		
88	--------------					
84	XXXXXXXXXXXXXX	LENS				
80					0	
76						
72		o o o	3.0mm			
68						
64						
60	--------------				0	
56						
52		o o o	3.0mm			
48						
44	--------------					
40					0	
36						
32						
28						
24						
20		o o o	3.0mm		0	
16						
12						
8						
4						
0	--------------				0	

FIGURE 10

STRATIGRAPHY PLOT

DATE:5/1/85   OBSERVER: BOYNE

ELEVATION:3200M TIME: 10:30   SLOPE: LEVEL

```
DEPTH  STRATIGRAPHY   GRAIN  GRAIN DENSITY  TEMP
(cm)                  TYPE   SIZE  (KG/M^3) DEG C
                             (mm)
------------------------------------------------------------
 116   -----------                  ^              ^
 112   -----------    . . .  <.5mm  |        0     |
 108                  . . .         |              |  ^
 104                                |              |  |
 100   XXXXXXXXXXX     MF           |              |  |
  96                               420             4  |
  92   XXXXXXXXXXX     MF     2mm   |        0     |  |
  88                  o o o         |              |  5
  84                                |              |  |
  80   -----------
       XXXXXXXXXXX     ICE          |              |  |
  76   XXXXXXXXXXX     LENS   2mm   -              -  |
  72   XXXXXXXXXXX                  ^        0        |
  68                                |                 -  ^
  64                  o o o         |                    |
  60                                |                    |
  56   -----------                  |                    |
  52                               346       0           |
  48                                |                    |
  44                                |                    6
  40                                |                    |
  36                                -                    |
  32                                         0           |
  28                  o o o                              |
  24                                                     -
  20
  16
  12                                         0
   8
   4
   0                                         0
```

FIGURE 11

Figure 12

END

FILMED

1-86

DTIC